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GEOLOGY

U–Pb LA–ICP–MS Age of Detrital Zircons from the Lower Riphean and Upper Vendian Deposits of the Luga–Ladoga Monocline

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Abstract—The results of LA–ICP–MS U–Pb analyses of detrital zircons from the Precambrian deposits of Luga–Ladoga monocline are discussed. The age spectra of the zircons separated from the Riphean to Upper Vendian sandstones from the Shotkusa-1 well demonstrate dominance of the Paleo- and Mesoproterozoic grains while the Archaean zircons are subordinate. The Riphean debris sources were local swells of the Northern Ladoga basement. The sequence interval presumably corresponding to the Vasilieostrov Formation (Upper Vendian) has yielded not only Paleo- and Mesoproterozoic zircon ages, but Neoproterozoic as well, implying a Timanide provenance: these zircons (527 ± 9 and 516 ± 13 Ma) allow deposition of a significant part of the Shotkusa-1 sequence at the very beginning of the Cambrian.

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Determination of the U–Pb isotope ages of detrital zircons has become an important method of paleogeographic and paleotectonic reconstructions, which led to appearance of the term "zircon revolution" [1]. In the region studied, such studies are still sparse [2–4], but they have already allowed substantial refinement of the stratigraphy and the features of sedimentation. Nevertheless, more reasonable reconstruction of the evolution of the Precambrian sedimentation requires further study, targeting the most ancient (Early Riphean) sediments. This work is intended to fill this gap partially and is devoted to recognition of the provenance sources for the Precambrian deposits of the Luga–Ladoga monocline applying analysis of the U–Pb isotope ages of detrital zircons from the Riphean to Upper Vendian sandstones, exposed by the Shotkusa-1 well located in the northern part of this structure in the area of Ladoga railway station (Oktyabrskaya Railway, Leningrad oblast, Fig. 1).

The sequence of the Shotkusa-1 well begins with the Lower Riphean sandstones of the Priozersk Formation [3]. According to [5], they belong to sub-litho-arenite and quartz arenite. Their detritus (quartz, microcline, and microquartzite) is slightly rounded and poorly sorted. The Priozersk Formation sandstone accumulated in the proximity of provenance sources in continental environments as a result of temporal flows [3].

The Priozersk Formation is overlapped with a sharp unconformity by silt–mudstones with layers and lenticular sandstone beds, attributed to the Starorussa Formation of the Upper Vendian [6, 7]. According to the classification [5], the sandstones belong to subarkose, sub-litho arenite, and quartz arenite. The deposits of the Starorussa Formation accumulated in the conditions of underwater fans and zones of weak currents and waves in shallow waters [8].

The rocks of the Starorussa Formation up the section of the Shotkusa-1 well are gradually replaced by the rocks of the Vasilieostrov Formation (Upper Vendian). In the westerly sections of the Luga–Ladoga monocline, the formations are separated by a disconformity [8]. The lower part of the Vasilieostrov Formation comprises subarkose sandstones with layers of tobacco–pink silty mudstones with an admixture of

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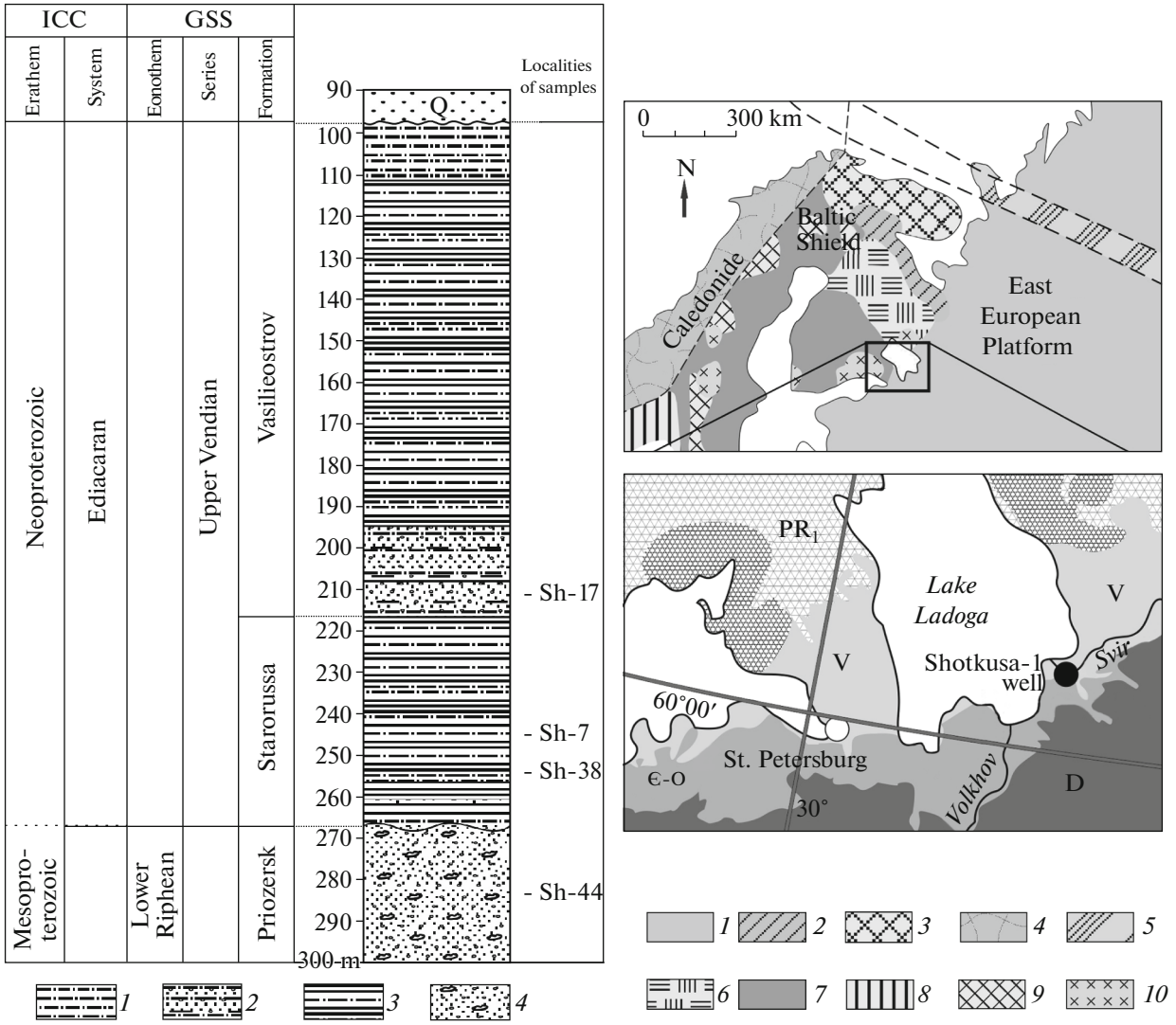

Fig. 1. Generalized stratigraphic section of the Luga–Ladoga monocline sediments (after [7, 8] with changes) and position of the studied samples (I, ultra fine- and fine-grained sandstones; II, siltstones; III, clays; IV, coarse-grained sandstones to gravelite); ICC, International Chronostratigraphic Chart; GSS, General Stratigraphic Scale of Russia; localities of the samples studied and their position in the simplified tectonic–geological scheme (*1*, Late Precambrian–Phanerozoic cover of the EEP and Phanerozoic complexes of the Pechora Plate; *2*, Belomorian mobile belt (1.96–3.7 Ga); *3*, Kola Geoblock (1.8–2.9 Ga); *4*, Caledonides; *5*, Timan Ridge; *6*, Fenno–Karelian Region (2.5–3.2 Ga); *7*, Svecofennian Region (1.65–2.1 Ga); *8*, Sveconorwegian Region (0.92–1.64 Ga); *9*, granitoids (1.66–1.86 Ga); *10*, rapakivi intrusions (1.44–1.67 Ga).

gravel-size grains of quartz and potassium feldspars. Its upper part is dominated by silty mudstones with beds of siltstones and fine-grained sandstones. Its deposition occurred under conditions of cyclic migration of shallow–marine facial belts under conditions of a relatively high sea level [8].

U–Pb LA–ICP–MS dating of the detrital zircons was carried out on four sandstone samples from the Shotkusa-1 well: (1) sample Sh-44, depth 285 m, Priozersk Fm; (2) sample Sh-38, depth 258.4 m and sample Sh-7, depth 248.3 m, Starorussa Fm; (3) sample S-17, depth 213 m, Vasilieostrov Fm (after [8]). The separation of zircons and preliminary sample preparation were carried out at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, by the standard procedure. U–Pb LA–ICP–MS dating of the zircon was carried out at the Institute of Geology, Siberian Branch, Russian Academy of Sciences (Ulan-Ude) using an Element XR (Thermo Scientific) mass spectrometer with a laser ablation unit UP-213 (New Wave Research) following common procedures [9]. The probability density plots of ages were constructed using an Isoplot 4.0 spreadsheet. In accordance with the accepted

approach [1], grains with a discordance of no more than 30% were taken into account. The distribution of U–Pb isotope ages of detrital zircons in all samples is shown in Fig. 2.

The Priozersk Formation sandstone (sample Sh-44) is dominated by Paleoproterozoic zircon grains (76%), forming a series of age maxima in the probability density plot (1700, 1859, and 1956 Ma). The zircon grains of Mesoproterozoic age (22%) form a single age cluster at about 1549 Ma. Zircons of Archaean age are scarce (<2%).

Three age groups of detrital zircons are distinguished in the sandstones of the lower part of the Starorussa Fm. (sample Sh-38): Mesoproterozoic (28% of grains) with a cluster at 1480 Ma, Paleoproterozoic (29% of grains, with clusters at 1849, 1951, and 2002 Ma) and Archaean (37% of grains, age clusters at 2667 and 2799 Ma). The sandstone of the middle part of this Formation (sample Sh-7) is, on the contrary, dominated by Paleoproterozoic detrital zircons (83%, maxima at 1780, 1928, and 1973 Ma). The grains of Mesoproterozoic age constitute about 11% of the population; they form a distinct age peak at 1561 Ma. The zircons of Archaean age here, in contrast to the sandstones of the lower part of the formation, are occasional. The predominance of the Paleoproterozoic zircons (92%) is also typical of the psammites of the upper part of the Starorussa Formation [4].

The population of detrital zircons in sample Sh-17 (base of the Vasilieostrov Formation) contains ~60% of grains with Mesoproterozoic ages; they form two clusters at 1256 and 1567 Ma. The zircons of Paleoproterozoic age (30% of grains) also form two maxima at 1864 and 1978 Ma. Furthermore, 4% of the Neoproterozoic grains have been recovered. They, like the occasional zircons of Archaean age, do not form any significant cluster. The three youngest grains of detrital zircons from sample Sh-17 have ages of 554 ± 15, 527 ± 9, and 516 ± 13 Ma.

These data show that in the Luga–Ladoga monocline the Lower Riphean and Upper Vendian deposits have significantly similar detrital zircon age patterns, as well as differences that allow reconstruction of changes in their provenance sources. The detrital zircons from the Priozersk Fm. sandstone and Vendian deposits demonstrate age clusters at about 1550–1570 Ma, which corresponds well to the time of crystallization of the Salma Pluton (1.55–1.53 Ga [10, 11]); it occurred about 150 km to the northeast of the studied area. Detrital zircons with ages from 1770 to 2100 Ma, which are present in different amounts in both the Lower Riphean and Upper Vendian sandstones, apparently evidence erosion of the Svecofennian intrusions in Northern Ladoga [12]. Considering the weak roundness and poor sorting of grains in the sandstones of the Priozersk Formation, it can be assumed that in the Early Riphean the detritus sources were located close to the sedimentation area.

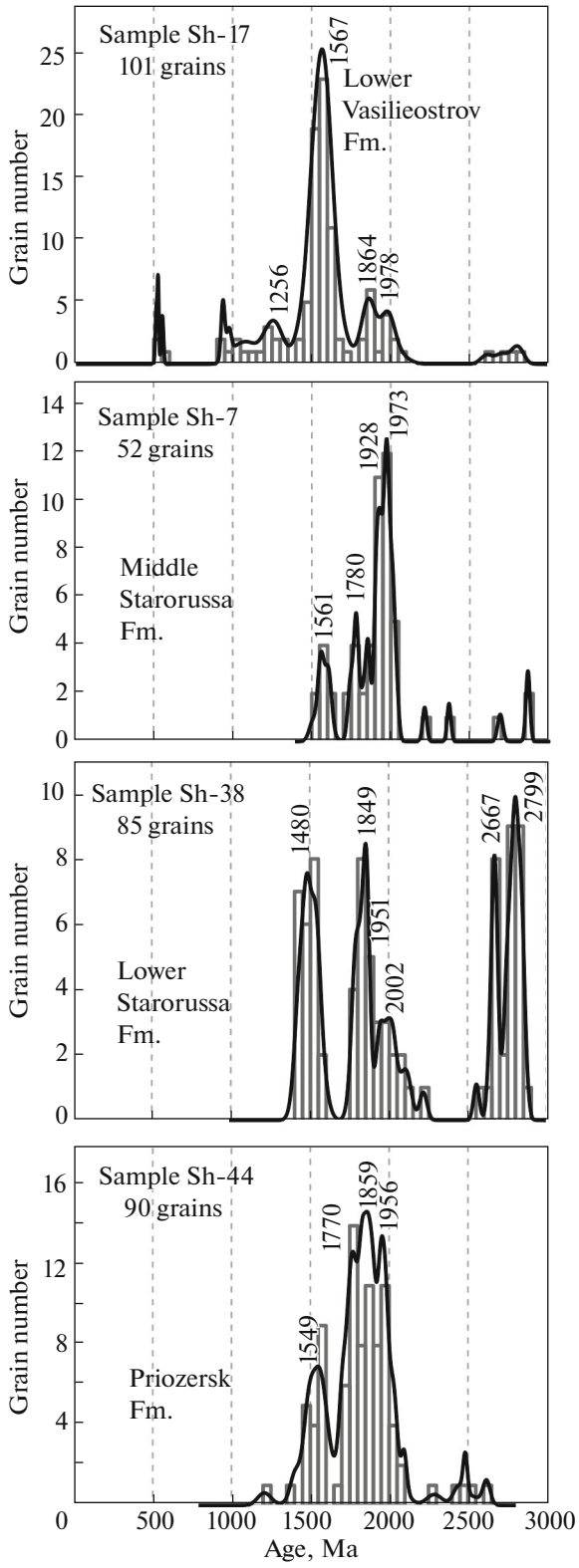

Fig. 2. Histograms and probability density curves for U–Pb isotope age distribution of detrital zircons from the Lower Riphean–Upper Vendian rocks of the Ladoga Monocline. The numbers show the age of clusters (Ma) formed by at least three results.

The sandstones of the lower part of the Starorussa Formation (Upper Vendian) contain Early Mesoproterozoic and Late Paleoproterozoic zircons, as well as a significant proportion of Archaean grains, probably derived from granite–gneiss domes in the northeastern part of the Pasha–Ladoga trough [12]. The sandstones in the middle part of the Starorussa Formation demonstrate a distribution of detrital zircon ages similar to that in the Lower Riphean rocks. This indicates either transport of the detritus, like in the Early Riphean, from closely located massifs or recycling of the Lower Riphean sediments. The latter seems more likely, considering the more mature composition of the Starorussa Formation sandstones.

The sandstones of the Vasilieostrov Formation comprise a large proportion of the Late Mesoproterozoic and Early Neoproterozoic zircons, although igneous rocks of these ages are absent in the Northern Ladoga [12]. On the contrary, zircons of approximately the same ages (1500–1000 Ma) occur in a significant amount in the Vendian and Cambrian rocks of the Timan Ridge [2] and the Lower Cambrian sediments of the eastern part of the Baltic monocline [4]. This suggests that already during accumulation of the Vasilieostrov Formation deposits, clastic material from the east begins to come to the study area. This is confirmed by the age distribution pattern of detrital zircons in sandstones of the Vasilieostrov Formation. For instance, according to [4], in the area of Sosnovy Bor (70 km west of St. Petersburg), the ratio of zircons of Paleo– and Mesoproterozoic ages in sediments is 73 and 25%, and in the vicinity of Lakhta (western outskirts of St. Petersburg), the number of zircons with the indicated ages is somewhat different 62 and 35%. In the Shotkusa-1 well located about 160 km to the east-northeast of St. Petersburg, i.e., closer to Timanide, the proportion of Paleoproterozoic zircons is reduced down to 30%, while the amount of Mesoproterozoic grains reaches 60%; apart from them, Neoproterozoic detrital zircons start to appear.

This study shows that in the Early Riphean the main sources of clastic material in the eastern Luga–Ladoga monocline were local basement uplifts of Paleo- and Mesoproterozoic ages located in the Northern Ladoga area, as well as the Salma Pluton of the rapakivi granites. At the beginning of the Late Vendian (Redkin Age), the sources of debris were (1) Palaeo- and Mesoproterozoic blocks of the basement; (2) the Lower Riphean sedimentary rocks of the Priozersk Formation apparently eroded, and at certain stages (for example, at the beginning of the Starorussa Age) Archaean blocks of the basement contributed some siliciclastics. This indicates a noticeable expansion of the provenance areas. During accumulation of the deposits of the Vasilieostrov Formation, along with the transport of erosion products from the Baltic shield into the sedimentation area, there was a significant amount of siliciclastics from the Timan Ridge.

The principal point of our studies, which undoubtedly requires further continuation, is the presence in the sandstones at the base of the Vasileostrovskaya Formation in the Shotkusa-1 well of detrital zircons with ages of 527 ± 9 and 516 ± 13 Ma (0.19% and 2.33% discordant, respectively). Although the presence of only two grains is not sufficient for a confident conclusion, this finding allows two possible explanations for their occurrence in the rocks of the Shotkusa-1 well, which are ascribed to the Upper Vendian. The first raises the question of the eligibility of recognition of the lower Vasilieostrov Formation sediments in the Shotkusa-1 well in the depth interval of 217–195 m [8, 13]: it well might be that here occur not Lower Kotlin sediments (Gdov), but variously grained sandstone–clayey deposits of the Voronkovo Formation (Upper Vendian) or even of the Lomonosov Formation (Lower Cambrian). The second suggests that a significant part of the Vasilieostrov Formation, which, together with the overlying Voronkovo Formation, corresponds to the Kotlin Formation of Kotlin Island and was considered by B.S. Sokolov [13] as a typical member of the Upper Vendian eponymous horizon, actually has an Early Cambrian age. The search for correct solution of this problem requires dating of detrital zircons from the sandstones of the Vasilieostrov Formation stratotype (Geolkom well, TSNIGR Museum, Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences) [7], as well as the Gdov sandstone itself.

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